3.0 METHODOLOGY FOR RELATIVE RISK ASSESSMENT

Risk assessment is a process that evaluates the likelihood that adverse ecological or human health effects will occur as a result of exposure to stressors (US EPA, 1998a). It is a process for organizing and analyzing data, information, assumptions, and uncertainties. Risk assessment involves identification of hazards or stressors, analysis of the linkage between exposure to stressors and effects on receptors, and risk characterization (US EPA, 1998a). Risk assessments are used to help risk managers determine priorities for actions that are designed to manage or reduce risk. Risk management is a decision-making process which involves such considerations as risk assessment, technological feasibility, statutory requirements, public concerns, and other factors.

In this study, the terms *risk analysis, risk characterization* and *relative risk assessment* refer to the processes of analyzing risks, describing risks, and the final comparison of relative risk assessment, respectively.

For this study, risk analysis and relative risk assessment of four different wastewater management options involved three steps:

1. Creation of a generic risk analysis framework (GRAF) for each wastewater management option
2. Conducting a risk analysis of each management option using the GRAF and characterizing the risk associated with each option
3. Comparing the risks associated with all four wastewater management options, based on the results of risk analysis of each management option, to arrive at a relative risk assessment.

3.1 Generic Risk Analysis Framework and Problem Formulation

In order to provide a consistent and comprehensive procedure for analyzing risk, a generic risk analysis framework (GRAF) was developed. The GRAF is a procedure for describing all potential risks and identifying all possible hazards, sources, exposure pathways, and effects on receptors, based on a generalized approach to the issue. This framework, also known as problem formulation, outlines potential issues to be analyzed for risk, using site-specific information. In this study, the GRAF was used to develop a conceptual model of potential risk for each management option. The GRAF incorporates human health and ecological risk components.

The use of a GRAF to analyze risks of individual wastewater management options is based upon the *Guide for Developing Conceptual Models for Ecological Risk Assessments* (Suter, 1996), a risk assessment framework outlined in EPA's *Residual Risk Report to Congress* (US EPA, 1999a), and EPA's ecological risk assessment framework, presented in *Guidelines for Ecological Risk Assessment* (US EPA, 1998a).

The first step in developing a GRAF is formulating the problem and developing a conceptual model of potential risk. In formulating the problem, the purpose for conducting the risk assessment is articulated, data are collected and assessed, and potential stressors, receptors, and exposure pathways are selected for further analysis. This information is then organized within a conceptual model, which is a "written description and visual representation of predicted relationships between ecological [or other] entities and the stressors to which they may be exposed" (US EPA, 1998a). For each wastewater management option, a conceptual model helps to define the information necessary to complete the risk analysis. The analyses necessary to characterize risk are then conducted as part of the next step, the option-specific risk analysis and characterization (see below).

Potential stressors include constituents of concern, such as compounds and elements, present in treated wastewater and their degradation byproducts or other derivatives. Potential secondary stressors include other effects of stressors that may pose additional risks themselves. Secondary stressors and the risks they pose can be particularly difficult to anticipate and describe.

Receptors are the human and ecological entities that are exposed to stressors and that may suffer potential adverse effects. Exposure to a stressor must be demonstrated before the linkage between a stressor and an adverse effect can be evaluated. Exposure pathways are the ways in which stressors and receptors are brought into contact with each other. Assessment endpoints provide yardsticks for measuring the effects of stressors. Important assessment endpoints selected for this study included drinking-water quality standards, surface- and marine-water quality standards, and other human health and environmental indicators. Where no assessment endpoints existed, potential adverse effects were evaluated using a weight-of-evidence approach.

3.2 Option-Specific Risk Analysis and Risk Characterization

The second step in risk assessment is conducting an analysis and evaluation of the conceptual model of risk for each wastewater management option. In this step, specific information concerning stressors, receptors, and exposure pathways is used to analyze relationships and anticipate potential adverse effects (or risks). In this study, such information included site-specific data on hydrogeology, water quality, wastewater treatment plant effluent, and wastewater management options used in South Florida. In order to evaluate exposure pathways, information concerning properties of stressors (for example, concentration, solubility, half-life, tendency to bioaccumulate) and the environment they pass through (groundwater, surface water, ocean, subsurface geology, and soils) were compiled and analyzed. Information about large-scale physicochemical processes that determine exposure pathways is also essential for determining whether receptors will actually be exposed to stressors. Such information was used to evaluate and refine the conceptual model for each wastewater management option.

Evaluation of the conceptual model involves an exposure analysis and risk characterization. Exposure analysis is critical to risk analysis and risk assessment; without exposure to a stressor, there is no risk (US EPA, 1998a). In this study, as the conceptual models were evaluated and refined, pathways that did not result in exposure of a receptor to stressors or exposure pathways that were insignificant or improbable were eliminated. Areas of uncertainty and data gaps were identified. Whenever appropriate, conservative assumptions were made that may result in overstating, rather than understating, exposure and risk. A conservative approach will be more protective of human and ecological health.

Risk characterization involves describing the potential adverse ecological and human health effects (risks) that may result from exposure to stressors (US EPA, 2000). Risks may be estimated, compared, or qualitatively described. In this study, risk characterization was performed at assessment endpoints for each conceptual model of a wastewater management option. Upon completion of the risk characterization, issues that pose actual risks were identified, while issues that pose little or no risk were eliminated or assigned lower priority in the final conceptual model of risk. Other risk factors were also taken into account, such as receptor sensitivity, response to change, and potential for recovery if the stress is removed or decreased (Brickey, 1995; GMIED, 1997).

3.3 Relative Risk Assessment

Risks and risk factors may be compared using a variety of methods; comparisons may be quantitative, semiquantitative, or qualitative. Frequently, such an assessment requires that professional judgment be applied to evaluate the relative magnitude of effects (US EPA, 1998a; Suter, 1999a, 1999b).

In this study, relative risk assessment relied upon results of the option-specific risk analysis and risk characterization to compare the risks and risk factors of the four wastewater management options. This relative risk assessment used a qualitative approach to prioritizing risk factors and describing the relative risks and risk factors. There are many risk factors that could have been used in the relative risk assessment. Risk factors were chosen on the basis of how they contributed to making useful comparisons between the potential risks to human and ecological health. Chapter 8 compares risk findings for each wastewater management option and discusses their priorities.

The following sections provide detailed descriptions of the risk methodology used.

3.4 Detailed Description of Problem Formulation

This study of relative risk develops conceptual models of risk that are based on the physical, chemical, and biological processes that govern the fate and transport of discharged wastewater constituents. Developing an understanding of such large-scale fate and transport processes is critical for providing the risk manager with the necessary information to make informed decisions on managing and decreasing risks. Without an understanding of the physical, chemical, biological, and human factors that influence risk, a risk manager may expend time and resources on managing risk symptoms without addressing and eliminating the causes of risk.

3.4.1 Selection of Potential Exposure Pathways

Once treated wastewater is released into the environment, the processes that determine fate and transport of wastewater constituents (stressors) define the large-scale nature of exposure pathways that must be evaluated. These large-scale processes act upon stressors in ways that are strongly governed by the specific chemical and physical properties of the stressors themselves. How these large-scale processes operate in the environments that receive discharges of treated wastewater also varies. Descriptions of the receiving environments (for example, groundwater, surface water, subsurface geology, and soils) are given in Chapters 4 through 7, which examine each of the wastewater management options in detail.

Advection, dispersion, and dilution are large-scale physical processes that play an important role in determining the transport of wastewater constituents. Advection involves mixing and transport by bulk movement of water and is often the single most important mechanism responsible for migration of wastewater constituents. Dispersion refers to slow spreading of constituents in response to gradients in concentration (molecular diffusion) and other phenomena. Dilution is a reduction in concentration of a stressor or other wastewater constituent, which may result from advection or dispersion.

In groundwater, the large-scale movement of wastewater constituents in the subsurface is strongly influenced by the characteristics of the geological media through which discharged effluent and groundwater flows. Porous media flow occurs where primary porosity exists, and it can result in widely varying rates of groundwater flow, depending on the size of pores, amount of pore space, and interconnection of pore spaces. Secondary porosity refers to larger fractures or solution channels in sediments or rock, where groundwater and effluent can move along solution channels, fractures, and other preferential flow paths. In such preferential flow, advective transport rates may be greater than porous media flow rates. In this case, dispersion frequently results from mixing at intersections of fractures and as a result of variations in fracture openings.

The eventual fate of wastewater constituents in the environment determines the final concentrations of stressors to which receptors may be exposed. *Attenuation* describes a variety of processes involving interactions between wastewater constituents and the environment that cause concentrations of constituents to decrease as time passes. Examples of processes that may result in attenuation include filtration, precipitation, settling, biological uptake, chemical transformation, dissolution and adsorption of constituents. Porous media may allow filtration of small bacteria and viruses, which can result in attenuation of these microorganisms, although very small microorganisms may be transported over long distances in porous media. Such attenuation may not occur if open fractures and solution channels are present, which may allow more rapid transport of both chemical compounds and microorganisms (US EPA, 1989).

Other important physical and chemical properties that influence the behavior of wastewater constituents include the stressor’s solubility in water; tendency to adsorb to soil, sediments or geologic media; and half-life. Wastewater constituents with higher solubilities may remain longer in effluent and groundwater and may also be present at higher concentrations in the initial effluent. The tendency to adsorb or bind to soil, sediments, or geologic media is determined by complex interactions between wastewater constituents and the physical and chemical environment. Adsorption of a constituent can result in retardation, or slowing, of the transport of stressors. For organic components, organic carbon partition coefficients (k_{oc}) provide measures of this tendency. Chapters 4 and 5 use such characteristics, in conjunction with distribution coefficients (k_d) and other measures, to determine rates of retardation for wastewater constituents.

The residence time of a compound or element in the environment is equivalent to the lifetime of the compound or element before attenuation or other processes cause it to dilute or disappear. The half-life ($t_{1/2}$) of a compound or element is the time required for it to decrease to half of its initial concentration. Half-life values take into account biodegradation and hydrolysis. Biodegradation is a geological process whereby microorganisms bring about chemical changes that can reduce the concentration of a specific wastewater constituent. Hydrolysis is a chemical reaction that adds water to the chemical structure of a compound, disrupting existing bonds or adding new bonds. Hydrolysis can increase solubility of a compound in water and enhance biodegradation, but it may also make a constituent more biologically available (Suthersan, 2001).

3.4.2 Definition of Potential Receptors

For this risk assessment, several potential receptors were selected. Drinking-water receptors are groundwater or surface-water resources that are potential receptors of underground or surface-water contaminants derived from treated wastewater. Potential drinking water receptors include underground sources of drinking water (USDWs), shallow public-water supply wells, private drinking-water wells, and some surface-water bodies used for drinking water sources (the latter are very uncommon in South Florida). Potential ecological receptors in surface water and ocean environments include organisms and ecosystems. Potential human receptors are people who may be exposed to treated wastewater constituents through recreational or occupational activities that bring them into contact with the disposed water.

3.4.3 Selection of Assessment Endpoints

The assessment endpoints chosen for this study are related to the type of receptor chosen. The first category of assessment endpoints pertains to USDWs and public and private drinking-water supply wells. For these drinking-water receptors, drinking-water standards were used as assessment endpoints. Federal drinking-water standards, also known as maximum contaminant levels, or MCLs, were designed to protect human health by establishing minimum standards for drinking water. MCLs are assumed to be protective of human health, although they may not be relevant to ecological standards. The Florida Department of Environmental Health (DEP) also regulates water quality of Class I surface waters intended for drinking water sources. In addition to treatment and disinfection requirements for the different wastewater management options, DEP regulations ensure protection of groundwater quality by establishing minimum criteria for groundwater according to Florida Administrative Code (FAC) 62-520.400.

Construction, operation, and monitoring of wastewater treatment facilities to certain standards are also considered in this category of drinking water-related assessment endpoints. All management methods are also subject to regulations concerning operation, maintenance, and monitoring.

The second category of assessment endpoints is used for ecological risk assessment in fresh surface-water bodies and the ocean. Surface-water quality standards for fresh water and marine water are intended to protect human recreation and ecological values. DEP regulations protect surface-water quality through an extensive set of regulations contained in FAC 62-302. These include state surface-water quality standards for fresh water and nearly marine or marine waters (Class III standards).

The third category of assessment endpoints addresses unregulated substances that may be present in drinking-water supplies, treated municipal wastewater effluent, and other water bodies. For unregulated substances, a weight-of-evidence approach was used, based on examination of the scientific literature concerning the effects of these substances. Examples of unregulated substances include emerging contaminants, such as hormonally active substances (endocrine-disrupting compounds), surfactants, and a wide range of other organic and inorganic compounds. Emerging contaminants are of concern because there is some evidence, based on a limited number of studies, that they may cause adverse effects in humans or other organisms. However, extensive and definitive testing under controlled conditions has generally not been conducted. Where possible, a range of concentrations that may have adverse effects is defined, and the concentration in USDWs or other water bodies is compared with this range-of-effects levels.

Assessment endpoints and the regulatory standards for surface water, groundwater, drinking water, and other operational standards are described more fully in Chapters 4 through 7 for each wastewater management option.

3.4.4 Selection of Potential Stressors

General characteristics of the potential human health or ecological stressors selected for this study are described in this section. Understanding the behavior and characteristics of stressors and their response to wastewater treatment is critically important in the analysis of risk. The stressors considered for this risk assessment were selected based on their occurrence in treated wastewater, scientific information concerning their toxic properties or other potential adverse effects, whether they are representative of a larger group of similar compounds, and their long-term fate in the environment.

In order to conduct a focused risk assessment, suitable representatives of each major category of stressors were chosen. Criteria for selection of representative stressors that might affect human health included severity of effects, level and efficacy of wastewater treatment, representative behavior, and whether the representative stressor provides a conservative (that is, protective) approach to evaluating risk. Contaminants of concern to public health also included substances for which human health effects are not yet fully understood, but for which there may be adverse human health effects, based on laboratory tests, observed effects, or other evidence.

General categories of human health stressors selected for this study include the following:

- Pathogenic microorganisms (for example, viruses, bacteria, protozoans)
- Inorganic compounds and elements (for example, metals and inorganic nutrients)
- Synthetic organic compounds (for example, pesticides and surfactants)
- Volatile organic compounds (VOCs)
- Hormonally active agents (for example, endocrine modulators and disruptors).

Representative ecological stressors that may cause adverse effects on organisms or ecosystems were selected based on a review of the scientific literature. Ecological stressors were chosen if they are known or suspected stressors to aquatic ecosystems, cause toxic effects in aquatic species, and are commonly found in wastewater effluent. Because many similar physical, chemical, and biological processes occur in both fresh-water and marine systems, the contaminants of concern are similar in both environments. Categories of ecological stressors selected for this study include the following:

- Inorganic compounds and elements (for example, inorganic nutrients and metals)
- Synthetic organic compounds (for example, pesticides, surfactants)
- Volatile organic compounds (VOCs)
- Hormonally active agents (for example, endocrine modulators and disruptors)
- Pathogenic microorganisms.

The general categories of human health and ecological stressors and the representative stressors selected to represent different stressor categories are listed in Table 3-1.

Table 3-1. Representative Human Health and Ecological Stressors Selected for this Study

Stressor Category	Representative Human Health Stressors	Representative Ecological Stressors
Pathogenic microorganisms	Rotavirus, total coliform, fecal coliform, enterococci, *Cryptosporidium parvum, Escherichia coli, Giardia lamblia*	*Cryptosporidium parvum*
Inorganic compounds (metals, metalloids)	Arsenic, copper	Arsenic, copper, lead, silver, cyanide
Inorganic nutrients	Nitrate, ammonia	Nitrate, total nitrogen, ammonia, total phosphorus, orthophosphate
Volatile organic compounds (VOCs)	Tetrachloroethene (PCE)	Tetrachloroethene (PCE)
Synthetic organic compounds (SOCs)	Chloroform (trihalomethanes) and chlordane (pesticides)	Methylene blue anionic surfactant (MBAS)
Hormonally active agents (endocrine-disrupting compounds)	Di(2-ethylhexl)phthalate (DEPH)	Estrogen equivalence

The characteristics of the selected stressors are described below.

3.4.4.1 Pathogenic Microorganisms

Microbial pathogens in water pose a high-priority public health concern (Raucher, 1996). In the United States, the number of microbiological diseases originating in contaminated drinking water is estimated to be as high as 40 to 50 million cases per year. While the total number of outbreaks of diseases caused by contaminated drinking water has decreased by 20% since the mid-nineties, the proportion of outbreaks associated with groundwater sources has increased by almost 30% (PSR, 2000). The emergence of new pathogens (for example, *Escherichia coli* O157:H7 and *Cryptosporidium parvum*), antibiotic-resistant strains of microorganisms, and a larger sensitive population have resulted in increased public health concerns (Rose et al., 2001). Microbiological diseases caused by ingestion of contaminated shellfish are included in this category of waterborne infections because contaminated water is often the major carrier (Wittman and Flick, 1995). Enteric microbial pathogens (that is, microbes that live in the intestinal tracts of humans and animals and that cause disease) present in wastewater are listed in Table 3-2.

Table 3-2. Microbial Pathogens Potentially Present in Untreated Domestic Wastewater

Bacteria / Helminths	Protozoa / Viruses
Bacteria	**Protozoa**
Campylobacter jejuni	*Cryptosporidium parvum*
Escherichia coli	*Giardia lamblia*
Legionella pneumophila	*Balantidium coli*
Salmonella typhi	*Entamoeba histolytica*
Shigella	**Viruses**
Vibrio cholerae	*Adenovirus* (51 types)
Helminths	*Astrovirus* (5 types)
Ancylostoma duodenale (hookworm)	*Calicivirus* (2 types)
Ascaris lumbricoides (roundworm)	*Coronavirus*
Echinococcus granulosis (tapeworm)	Enteroviruses (72 types)
Enterobius vermicularis (pinworm)	Hepatitis A
Necator americanus (roundworm)	Norwalk agent
Schistosoma	*Parvovirus* (3 types)
Strongyloides stercoralis (threadworm)	*Reovirus* (3 types)
Taenia (tapeworm)	Rotavirus (4 types)
Trichuris trichiura (whipworm)	

Source: York et al., 2002.

Depending upon the level of treatment and disinfection, concentrations of microbial pathogens in treated wastewater discharged to the environment can vary widely. An aggressive treatment combines disinfection with filtration to kill or physically remove microbial pathogens present in drinking water. For example, most bacteria and viruses in wastewater are generally effectively inactivated by disinfection with chlorine and filtration (York et al., 2002). However, disinfection byproducts, such as trihalomethanes, that are formed when chlorine reacts with organic compounds can pose human health concerns as well.

Survival of pathogenic microorganisms in soil and water generally is limited to days, weeks, or months, depending on the microorganism and whether it can form cysts or spores that persist in the environment. Survival is affected by factors such as temperature, availability of water and oxygen, and whether an animal host is needed for survival or growth of the microorganism. There is a small but growing body of information concerning survival of pathogenic microorganisms in the shallow subsurface and other microbial processes in geologic formations such as microbial denitrification in the shallow subsurface in northeast Florida (USGS, 2000). If viruses are not inactivated by treatment and are released, their small size and longevity may allow them to be distributed widely through the environment. Viruses may survive in surface water and groundwater, although most viruses typically cannot reproduce outside the human host (PSR, 2000). Viral contamination of wells, especially private wells with no treatment, poses concerns.

Potential human exposure pathways to pathogenic microorganisms include the following:

- Ingestion of water contaminated by exposure to wastewater
- Ingestion of contaminated food (such as shellfish, fish, produce, or foods processed in contaminated water)
- Dermal contact with contaminated water or soil through swimming, showers, spray irrigation, or occupational exposure
- Inhalation of contaminated water or soil (aerosols, shower spray, spray irrigation, dust, occupational exposure).

Secondary spread may also be possible, which includes person-to-person contact, use of public swimming facilities, and transmission from food handlers and care facilities (Chick et al., 2001).

Microbial growth in groundwater is not well characterized in general because of the difficulty of obtaining microbiologically representative samples without introducing surface contaminants. There are many gaps in knowledge concerning potential human health effects from ingestion of pathogenic microorganisms in water:

- Whether indicator organisms for microbial pathogens, such as coliform, are representative of pathogenic microorganisms
- Whether environmental sources other than wastewater exist for pathogenic microorganisms
- Exposure factors
- Modes of transmission
- Modes of environmental transport of microorganisms
- Survival potential of microorganisms in groundwater.

Three representative pathogenic microorganisms were selected to evaluate human exposure to treated wastewater: rotavirus, *Cryptosporidium parvum,* and pathogenic strains of *Escherichia coli* (*E. coli*). These are described below.

<u>Rotaviruses</u>

Rotaviruses are highly infective viruses that can be transmitted in water, causing a highly contagious disease that induces vomiting and diarrhea. In the United States, rotavirus has been estimated to cause 3 million cases of childhood diarrhea, resulting in 500,000 doctor visits, 100,000 hospitalizations, and up to 100 deaths annually (EHP, 1998a; SAIC, 2000). Because of the easily transmitted and highly contagious nature of the illness, rotaviruses were selected as a representative of pathogenic enteric viruses.

Other enteric viruses that are associated with poor-quality or untreated wastewater have been detected in near-shore waters and canals, including coxsackie viruses, Hepatitis A viruses, and Norwalk-like virus (Rose et al., 2000). These viruses, if ingested, can cause diarrhea, aseptic meningitis, and myocarditis. Their small size (in the nanometer range) and structure enhances viral survival and transport in water; these viruses can survive in groundwater for more than 2 months (Rose et al., 2000). Plankton and marine sediments may serve as reservoirs for pathogenic microorganisms, which can emerge to become infective when conditions are favorable (Henrickson et al., 2001).

Cryptosporidium parvum

Cryptosporidium parvum, an enteric protozoan, is considered to be a major risk to U.S. water supplies because it is highly infectious, forms cysts and oocysts that are resistant to chlorine disinfection, and is difficult to filter because of its small size. *Cryptosporidium* poses significant challenges to public health and water authorities (Gostin et al., 2000). If it is present in drinking water, it poses a high risk of waterborne disease (particularly for immunocompromised individuals). There have been 12 documented waterborne outbreaks of *Cryptosporidium* in North America since 1985; in two of these (Milwaukee and Las Vegas), mortality rates among exposed immunocompromised individuals ranged from 52% to 68% (Rose, 1997). Similar enteric protozoans include *Giardia lamblia*, *Entamoeba histolytica*, and *Balantidium coli* (York et al., 2002).

Protozoan cysts and oocysts are very persistent in the environment, particularly where water exists. Dormant oocysts may remain viable for months in sewage or groundwater until they find a new host. *Cryptosporidium* infects both humans and animals and can be transmitted through ingestion of contaminated water or food. Secondary infection can also occur. *Cryptosporidium* forms a reproductive oocyst that, once ingested, continues its life cycle in the gastrointestinal tract, causing the disease Cryptosporidiosis. The parasite can also be spread through the fecal-oral route by infected food handlers or in day-care settings. As few as 10 to 25 oocysts can cause infection; however, the disease is usually self-limiting with 2 to 10 days of symptoms in healthy persons. In sensitive populations and individuals, the disease can be life threatening.

Chlorine, the traditional water disinfectant for killing water-borne pathogenic bacteria and viruses, is not as effective against *Cryptosporidium* as other waterborne organisms, for example, *Giardia* (Joyce, 1996). Standard screening methods have proven ineffective as well. Filtration is the accepted method of removing *Cryptosporidium*.

Because of the severity of the disease, its widespread occurrence in nature, and because water and wastewater treatment does not always address *Cryptosporidium*, it was chosen for use as a representative pathogenic protozoan for evaluating human health risks from pathogenic protozoans in discharged treated wastewater.

Fecal Coliforms (*Escherichia coli*)

Fecal coliforms are bacteria that are normally found in human and animal wastes. *Escherichia coli,* or *E. coli*, is a type of fecal coliform bacteria. The presence of *E. coli* in water is a frequently used indicator of recent sewage or animal waste contamination, although it is not a reliable indicator of human sewage. It is important to note that sewage-indicator bacteria such as fecal coliforms have short survival times in the environment and may not be good indicators of the presence of protozoans and viruses in some environments (Henrickson et al., 2001). For example, one injection well monitoring study performed in Florida found that indicator bacteria and coliphages were not detected, while *Cryptosporidium* oocysts were detected at very low concentrations (Rose et al., 2001).

Most strains of *E. coli* are harmless and live in the intestines of healthy humans and animals without causing illness. However*, E. coli* O157:H7 is one strain of *E. coli* that produces a powerful toxin that can cause severe gastrointestinal illness. Infection by *E. coli* O157:H7 may cause hemolytic uremic syndrome, in which red blood cells are destroyed and kidney failure occurs. About 2% to 7% of infections lead to this complication. In the United States, most cases of hemolytic uremic syndrome are caused by *E. coli* O157:H7 (US EPA, 2001a). Exposure may occur through ingestion, recreational contact, or consumption of contaminated water or food (Schmidt, 1999). Sensitive human receptors include children, the ill, the immunocompromised, and the elderly. Because of the severity of illness that may occur upon exposure to *E. coli* O157:H7, fecal coliforms were selected as a representative human health stressor.

Pathogen fate, transport, and survival in the environment are discussed more in Chapter 4. Data on concentrations of pathogenic and indicator microorganisms in treated wastewater and from groundwater monitoring are provided in Appendix 1 (Appendix Tables 1-3, 1-4, and 1-5).

3.4.4.2 Inorganic Stressors

Wastewater contains a large number and variety of inorganic constituents, including metals, salts, nutrients, and other substances. Many, if not all, of these inorganic constituents are natural in origin (that is, they are ultimately derived from natural materials and are not "manmade" in the sense of being synthesized by humans), but their concentrations in wastewater may be elevated because of human activities. Many inorganic substances, if present at high enough concentrations, can pose some risk to human health. For this reason, many drinking-water standards (maximum contaminant levels, or MCLs) address the maximum amount of a given inorganic substance allowed in drinking water. Removal of these constituents will depend upon the level and type of wastewater treatment that is used.

Metals

Like nutrients, metals are naturally occurring and play a necessary biological role in the environment. However, in excessive amounts, metals can be toxic to wildlife, fish, and aquatic organisms. Metals have complex and dynamic physical and chemical reactions in the environment and can occur in different chemical forms or species. Metal speciation is important in understanding biological uptake by fish and wildlife. Factors that affect chemical speciation of metals include pH, alkalinity, the presence of organic matter and colloidal particles, and the oxidation-reduction potential of the environment (Stumm and Morgan, 1981). Organisms also differ in their capacity to store, remove, and detoxify metal contaminants (Wallace and Braasch, 1997).

Copper is an example of an essential micronutrient metal that is required by plants, animals, and most microorganisms in trace amounts. However, at higher concentrations, copper is toxic to algae, inhibiting growth and photosynthesis; copper sulfate and other copper-containing compounds have been used to control algal blooms in fresh water bodies and reservoirs since the early 1900s. The bioavailability of copper, or its ability to be taken up by organisms, depends in large part on its speciation. Total copper is not a good measure of bioavailablity. Reduced copper, or Cu^{2+}, is more readily taken up by organisms than the oxidized form and is therefore a better indicator of potential stress.

Arsenic is a metalloid element that is often present in groundwater where underlying rocks and soil contain arsenic salts or arsenic-containing minerals. A variety of industrial and agricultural activities also generate or release arsenic-containing compounds, including production and use of wood preservatives (for example, copper chromium arsenate), mining of arsenic-containing ores, and manufacture and use of arsenic-containing pesticides (for example, lead arsenate). Since arsenic is highly soluble, particularly under reducing conditions (which are often found in groundwater), it may also be highly mobile. Movement of surface water and groundwater provide important potential transport pathways for arsenic and other metals.

Chronic arsenic exposure causes a variety of human health effects, including carcinogenic and noncarcinogenic effects (Chowdhury et al., 2000; Morales et al., 2000). The population cancer risks from arsenic in U.S. water supplies may be comparable to those from environmental tobacco smoke and radon in homes (Smith et al., 1992). Noncarcinogenic effects of low levels of arsenic include adverse effects on the gastrointestinal system, central nervous system, cardiovascular system, liver, kidney, and blood (Abernathy et al., 1999; Tseng et al., 2000; Kaltreider et al., 2001; and Hopenhayn-Rich et al., 2000). At higher oral doses (600 milligrams per kilogram per day or more), poisoning and death will result.

Human exposure to inorganic arsenic results primarily from ingestion of contaminated drinking water or ingestion of contaminated food. Examples of food that can contain elevated arsenic levels include fish, shellfish, crustaceans, and some cereals, such as rice, taken from water or soils with high arsenic concentrations. Consumption of fish and shellfish from waters that contain elevated amounts of arsenic may be an important source of arsenic in humans. In food, the highest levels of arsenic in the U.S. Food and Drug Administration’s total diet survey were found in fish, with a mean level of about 15 parts per million (ppm) As_2O_3 in the edible portion of finfish (Jelinek and Corneliussen, 1977).

Approximately 5% of large and small regulated water-supply systems in the United States are estimated to have arsenic concentrations that exceed 20 micrograms per liter (µg/L) (Morales et al., 2000). The MCL for arsenic was formerly 50 parts per billion (ppb). In January 2001, the EPA lowered the MCL to 10 ppb. This lower standard was reviewed in 2001 and early 2002. After considerable public comment and deliberation, the 10 ppb MCL level was determined to be appropriate, and the Final Arsenic Rule went into effect in February 2002. The World Health Organization also recognizes an arsenic standard for drinking water of 10 ppb.

In the marine environment, arsenic typically occurs in seawater at concentrations ranging from 1 to 8 ppb and in sediments at 2 to 20 ppm. The distribution of arsenic in terrestrial environments is not nearly so homogeneous, as indicated by the higher levels of arsenic in marine organisms than terrestrial organisms; the biological concentration factor may vary by orders of magnitude between aquatic and terrestrial organisms (Fishbein, 1981). Arsenic may bioaccumulate in aquatic organisms. However, there is considerable variability in aquatic food-web bioaccumulation (Penrose et al., 1977; Vallette-Silver et al., 1999; Woolson, 1977). Organisms containing high levels of arsenic tend to be those that ingest sediment particles while feeding; that is, benthic filter-feeders or detritus-feeders exhibit higher concentrations of arsenic than pelagic fish.

As with copper, factors that govern biological effects of arsenic include its bioavailability, the quantity ingested or respired, the degree of assimilation, and the extent of retention in tissues.

Gaps in knowledge concerning arsenic and human health and ecological effects concern detailed transport mechanisms, mobility in the environment, carcinogenesis, whether there are cumulative or synergistic effects in combination with other contaminants, differences in bioaccumulation by different species, and the proper dose-response relationship to use in ecological risk assessment.

Inorganic Nutrients

Wastewater is a source of nutrients such as nitrogen, phosphorus, and other substances that act as nutrients. Secondary treatment removes only a portion of the nitrogen and phosphorus that may be present (see Chapter 2).

Nitrogen is the most important nutrient to consider in an ecological risk assessment for a marine environment because nitrogen limits primary production in marine environments. While many studies focus on total nitrogen (all forms of nitrogen), nitrate is the form that is most readily available for uptake by algae and plants. Excess nitrate in drinking water can potentially affect the health of infants, young children, and pregnant women and can cause methemoglobinemia (Knobeloch et al., 2000; Gupta et al., 2000). Human exposure to excess nitrate can occur through drinking or accidentally ingesting water that has elevated concentrations of nitrate. Little is known about the potential health effects of long-term exposure to excess nitrate in drinking water. Some studies of chronic nitrate ingestion have suggested connections to reproductive and developmental health effects, certain cancers, childhood diabetes, and thyroid disease.

The Safe Drinking Water Act established an MCL for nitrate of 10 milligrams per liter (mg/L), or 10 parts per million (ppm). This federal standard is used to ensure the safety of public water supplies, but does not apply to private wells. An estimated 2 million private household water supplies in the United States today may fail to meet this federal standard for nitrate (Knobeloch et al., 2000).

Excessive nitrate in the marine environment can stimulate phytoplankton and macroalgal growth. This can create adverse effects such as eutrophication (reduction of available oxygen), loss of eelgrass, dead zones because of low dissolved oxygen concentration from decomposing organic matter, and increases in harmful algal blooms (Nixon, 1998; Joyce, 2000). It is important to note that the 10 ppm drinking water standard for nitrate is generally much higher than the concentration of nitrate typically present in seawater or coastal waters, which ranges from several tenths of a part per million to several parts per million.

Excess nutrients may create secondary stressors, such as harmful or nuisance algal blooms. The algal toxins that may be produced by harmful algal blooms (HABs) can cause adverse effects on humans, aquatic mammals, fish, shellfish, and other organisms. Human ingestion of seafood contaminated by HABs can result in respiratory illness, gastroenteritis, and skin irritation. Paralytic shellfish poisoning is one example of an illness caused by toxin-producing dinoflagellates that form red tides. However, most scientists agree that, although excess nutrients may be a factor in some blooms, other environmental factors such as changes in temperature or circulation may cause many algal blooms (Tibbetts, 2000).

Phosphorus is a nutrient of concern in freshwater ecosystems because it is frequently the limiting nutrient for algal and plant growth, in contrast to nitrogen which tends to be the limiting nutrient in marine waters. Excess phosphate in freshwater can cause excessive algal growth, eutrophication, and low dissolved oxygen, just as excess nitrate in coastal waters can result in similar effects. Excess phosphate already exists in many of South Florida’s fresh water aquatic ecosystems, and a phosphate-based water quality standard is being considered for Lake Okeechobee, which is heavily affected by fertilizer runoff from adjacent agricultural lands.

Different forms of phosphorus exist in the aquatic environment; the most important are orthophosphate, total phosphorus, and particulate phosphorus. Orthophosphate (also known as soluble reactive phosphorus) is the major inorganic form of dissolved phosphorus most readily available for biological assimilation. Total phosphorus, as the name implies, refers to all the phosphorus in a volume of water including dissolved and particulate forms. Orthophosphate was chosen as a representative nutrient stressor in fresh water ecosystems.

3.4.4.3 Organic Compounds

Pesticides

Pesticides in wastewater primarily originate from stormwater runoff from lawns and gardens and other areas where pesticides are used. Human exposure to pesticides can occur through ingestion of contaminated drinking water, food, or dermal contact with contaminated water (Moody and Chu, 1995). Potential human receptors include adults, children, subsistence fishermen, farmers, and sensitive portions of the population, such as the elderly and ill. A number of pesticides, including chlordane, were evaluated for deep-well injection, while chlordane alone was used as a representative pesticide in other wastewater management options.

Chlordane is a chlorinated insecticide that was widely used in agricultural, industrial, and domestic applications; about one-third of the chlordane used in the United States was applied to control pests in homes, gardens, lawns, and turf (ATSDR, 1995). The EPA in 1983 banned all use of chlordane, except for control of termites. In 1988, because of concerns about carcinogenicity, toxicity, and harmful effects on wildlife, the EPA banned its use except for fire-ant control in power transformers. Chlordane is no longer distributed in the United States.

Despite having been banned years ago, chlordane is extremely persistent in the environment and may remain in soil for 20 years (ATSDR, 1995a). It is associated with many human health effects: chlordane may be carcinogenic, toxic, and impair human immune and neurological systems (IARC, 1997; Hardell et al., 1998; Kilburn and Thornton, 1995). Gaps in knowledge concerning human health risks posed by chlordane include the effects of long-term, low-dose exposure, whether it is carcinogenic, and whether it affects fertility, development, or neural systems.

Chlordane binds strongly to particles, does not dissolve easily in water, and may concentrate in the surface microlayer of surface water or in aquatic sediments. Because it is highly lipophilic, chlordane bioaccumulates in aquatic organisms. For compounds such as chlordane, groundwater transport is minimal (Thomann, 1995). The solids on which the chemical is adsorbed are stationary for the most part in groundwater. In surface water, the solids are transported during advection, and there may be significant interactions with aquatic sediments (Thomann, 1995).

Volatile Organic Compounds

Tetrachloroethene (PCE) is a VOC that may be formed in small quantities during chlorination of water or wastewater. Due to its volatility, tetrachloroethene does not remain long in surface or marine waters and will evaporate to the atmosphere; therefore, it has little potential for accumulating in aquatic organisms (US EPA-OW, 2002). However, in groundwater, tetrachloroethene is very mobile and persistent, which enables it to travel significant distances. Research studies have concluded that PCE-contaminated drinking water can be linked to elevated incidence rates of leukemia, bladder, lung and colorectal cancers in humans and experimental animals.

Human exposure pathways for VOCs could include drinking water, ingestion of water during recreational or occupational activities, and exposure to vapor in water. Potential human receptors include private well owners, who may be operating wells that are neither monitored nor treated to national drinking water standards.

The Florida Class III Marine water quality standards for tetrachloroethene are ≤8.85 μg/L on an annual average. The estimated half-lives of trichloroethylene (3.2 μg/L) from an experimental marine mesocosm during the spring (8 to16ºC), summer (20 to 22ºC), and winter (3 to 7ºC) were 28, 13, and 15 days respectively (Wakeham, et al., 1983, in Montgomery, 2000). Toxicity tests indicate toxic levels range from 22 mg/L (LC_{50} (24 hours) for *Daphnia magna* (LeBlanc, 1980, in Montgomery, 2000) to 3,760 milligrams per kilogram (mg/kg) acute oral LD_{50} in rats (TECS, 1985, in Montgomery, 2000).

Surfactants

Gaps in knowledge concerning the human health effects of surfactant compounds in drinking water include the effects of chronic low-dose exposures, suitable critical endpoints for risk estimates to represent sensitive populations, and the exact biological mechanisms by which these compounds affect human health.

Surfactants were chosen as a potential ecological stressor to evaluate because of their widespread use, occurrence in wastewater, their effects upon organic matter, and the relative lack of information concerning their ecological effects, in comparison to compounds currently regulated under the Safe Drinking Water Act. Surfactants are found in laundry detergents and in wastewater and are known to persist in wastewater, sewage sludge, and the environment (Dental et al., 1993). Surfactants have also been suggested as a potential precursor to an endocrine-disrupting agent or estrogenic substance. Estrogenic substances, such as alkylphenol-polyethoxylates (APE), and other alkylphenols, such as nonylphenol, in sewage effluent may also originate from biodegradation of surfactants and detergents during wastewater treatment (Purdom et al., 1994 and Jobling and Sumpter, 1993, both in US EPA, 1997). The representative surfactant chosen for this study is methylene blue anionic surfactant (MBAS), which is an anionic surfactant found in commercially available detergents (Dental et al., 1993).

Hormonally Active Agents

Estrogenic hormones and potential endocrine disrupters include pharmaceuticals (for example, estrogens and their degradation products), surfactants, some pesticides, dioxins, and plasticizers. Scientific opinion is mixed concerning whether such compounds disrupt normal endocrine function, reproductive and developmental processes, or immunological processes (Birnbaum, 1994; Colborn, 1995; vom Saal, 1995). Not all scientists agree that exposure to hormonally-active agents represents cause for alarm. Authors of one paper reported that "there is little direct evidence to indicate that exposures to ambient levels of estrogenic xenobiotics are affecting reproductive health" (Daston et al., 1997). In addition, they state that "estrogenicity is an important mechanism of reproductive and developmental toxicity; however, there is little evidence at this point that low level exposures constitute a human or ecologic risk." The picture regarding hormonally active agents is therefore complex.

Hormonally active agents found in wastewater and in surface water elsewhere include estradiols (an active component of oral contraceptives), as well as alkylphenols (biodegradation products of nonionic surfactants). Industrial and pharmaceutical compounds with hormonally active effects include butylbenzylphthalate (BBP), di-n-butylphthalate (DBP), tributylphosphate, butylated hydroxyanisole (BHA), dimethylphthalate, and 4-nonylphenol, dioxin (2,3,7,8-TCDD), bisphenol A, PCBs, PBBs, pentachlorophenol, penta- to nonylphenols, phthalates, and styrenes (Daughton and Ternes, 1999; Jobling et al., 1995).

Scientific studies suggest that these chemicals may cause adverse effects in aquatic organisms and that wastewater is one source of such chemicals (Rodgers-Gray et al., 2000; Nichols et al., 1998). Studies in Florida have documented potential endocrine exposure effects on the Florida panther (Facemire et al., 1995) and American alligator (Semenza, 1997). However, the sources of endocrine disruptors were not documented in these studies.

These substances have been identified in concentrations in the nanograms-per-liter (or parts-per-trillion) range in secondary-treated municipal wastewater effluent and receiving waters (Huang and Sedlak, 2000; and Harries et al., 1998). Because these substances are often highly soluble in water, they may be difficult to remove using conventional technology; estrogenicity has been identified primarily in the water-soluble fraction of wastewater (Raloff, 2000). Municipal wastewater treatment may remove these compounds if they are associated with other organic particles or substances that are removed by treatment.

Environmental monitoring indicates that such chemicals can be present in drinking water as well (Potera, 2000). Potential human exposure pathways include ingestion of water containing such substances, dermal contact with water, and inhalation of volatile compounds from water vapor. Potential human receptors include people consuming or drinking water containing such substances and those exposed to such water as a result of recreational or occupational activities, including subsistence fishermen and farmers.

Significant gaps in knowledge exist concerning the human health and ecological effects of these compounds because they have only recently been recognized as potential contaminants of concern. Comprehensive and long-term epidemiological studies are needed to critically evaluate the effects of exposures to these compounds. Other gaps in knowledge include the concentrations of hormonally active substances in treated municipal wastewater effluent, whether they present an ecological concern, effects of exposures to mixtures, and cumulative effects of all sources of such compounds. Better monitoring methods need to be developed in order to conduct such studies.

The EPA requires testing of commercial chemicals to determine their endocrine disruption potential. Screening techniques to test chemicals for endocrine disruption are being developed. Because of the relative newness of the science, no regulatory guidelines have yet been established for concentrations of hormonally active agents in wastewater.

The hormonally active substance selected to evaluate potential human health risk was di(2-ethylhexyl)phthalate, or DEPH. DEPH is a plasticizer, used to make polymers (such as PVC) flexible. The threshold limit value for constant 8-hour exposure in air (OSHA, ACGIH) is 5 ppm. DEPH poses some human health concerns, but because it is mostly insoluble in water and is biodegradable in small quantities, it is not considered a critical ecological risk stressor. Large quantities can cause liver damage and reproductive problems in lab animals, but the effects are reversible if the stressor is removed.

One advanced wastewater treatment plant in South Florida also provided data on estrogen equivalence in treated wastewater. Estrogen equivalence is a measure of the response of breast cancer cells to exposure to strongly estrogenic substances, such as hormone replacement and birth control pills (Frederic Bloettscher, Consulting Professional Engineer. September 13, 2001. E-mail communication to Jo Ann Muramoto, Horsley & Witten, Inc.).

3.5 Analysis Plan

This relative risk assessment focused on characterizing and evaluating the major fate and transport processes that determine where the vast majority of discharged effluent and effluent constituents will end up. The focus is on the major exposure pathways that could lead to potential exposure of receptors to effluent constituents that act as stressors.

One of the goals of the risk assessment team was to determine whether final dilutions of wastewater stressors could be predicted or modeled for the ends of major exposure pathways (that is, at the USDW, surface water, or ocean receptors). There are many other potential sources of these stressors in the South Florida environment; wherever possible, evidence linking the stressor to the wastewater management option was sought. Analysis of fate and transport pathways is particularly important for singling out the concentration of stressors that can be ascribed to discharged treated wastewater. Without an analysis of fate and transport, it would be difficult to rule out other sources of the same stressor in surface-water receptors or the ocean or even in drinking-water receptors, such as the USDW or surficial aquifer.

In order to evaluate human health risks, concentrations of representative stressors in treated wastewater at the treatment plant and in drinking water or other receptors were compared with the assessment endpoints: drinking-water standards such as the federal drinking-water standards (MCLs) or Florida's water quality standards for Class I waters intended to protect drinking-water sources. If there was no human exposure pathway involving a particular water resource, then the standards for that pathway were not used (for example, as there is no human exposure pathway involving ingestion of seawater, then the drinking-water standards were not used). To evaluate ecological risks, monitoring data for treated wastewater were likewise compared with water quality standards intended to protect ecological values. Examples include Florida's regulations pertaining to Class III coastal and marine waters.

For unregulated compounds, a weight-of-evidence approach based on general scientific literature was used to determine whether disposal of treated wastewater containing such compounds could pose a risk to human health or aquatic ecosystems.

3.6 Final Conceptual Model of Probable Risk

When the conceptual model of potential risk was evaluated using site-specific information, stressors, receptors, or exposure pathways that were insignificant or improbable were eliminated. Criteria for elimination of exposure pathways, stressors, or receptors included the following:

- The transport or exposure pathways that would expose a receptor to a stressor never or hardly ever exist or occur
- The time it would take for a stressor to be transported from the discharge point to the receptor is longer than the residence time of the stressor in the environment
- Wastewater treatment or other attenuation processes routinely decrease the concentration of a particular stressor well below required standards or assessment endpoints
- Attenuation processes that would in all probability result in a significant decrease in concentration of a stressor are known to exist in the receiving environment
- A receptor does not exist in the receiving environment
- There is little or no evidence that adverse effects occur from exposure of receptors to stressors, despite the fact that exposure must occur, using site-specific information.

The risk to human health or the environment from stressors in treated effluent was described to be nonexistent to very low, when either of the following occurs—

- A stressor, receptor, or exposure pathway is eliminated
- It is demonstrated that adverse effects do not occur.

The risk was judged to be low or moderate when any of the following occurs—

- There is a small chance of exposure
- Assessment endpoints (standards) are usually but not always met
- Adverse effects are possible.

The risk was judged to be moderate to high when any of the following occurred—

- There is a moderate-to-high chance of exposure
- Assessment endpoints were almost always exceeded for some stressor
- Adverse effects can occur.

The risk was judged to be very high when there is a high chance of exposure and monitoring indicates that adverse effects have already occurred.

The final conceptual model for each option describes in narrative form the risk findings and conclusions for each wastewater management option.

3.7 Relative Risk Assessment

The risk findings for each wastewater management option were compared and evaluated. Ecological and human health risk factors were compared across all four wastewater management options. A final set of criteria for risk prioritization was developed. The product of the relative risk comparison of wastewater management options is a prioritized list of risk factors for each wastewater management option.

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